

Annealing effect on the Giant magnetoimpedance of amorphous microwire

K Mandal^{1*}, S Pan Mandal² and M Vázquez³

¹C K Majumdar Laboratory, S N Bose National Centre for Basic Sciences, Block JD, Sector III, Salt Lake, Kolkata-700 098, India

²BSB Limited, 6 Colootola Street, Kolkata-700 073, India

³Instituto de Ciencia de Materials de Madrid, CSIC, Campus de Cantoblanco, 28049 Cantoblanco, Madrid, Spain

E-mail. kalyan@bosc.bosc.res.in

Abstract : Giant magnetoimpedance (GMI) effect in positive magnetostrictive glass-coated amorphous $\text{Co}_{83}\text{Mn}_{17}\text{Si}_{1.8}\text{B}_{1.1}$ microwire has been studied as a function of a dc magnetic field $-140 < H_{dc} < 140$ Oe and frequency $0.1 < f < 12.85$ MHz. A maximum change of 43% in MI of the as-quenched sample has been observed around 5 MHz frequency. Heat treatment of the sample by passing a dc current of 50 mA through it enhances the MI value to a large extent (maximum change ~94%) by increasing the outer domain volume and inducing a transverse anisotropy. The magnetization of the as-quenched and heat-treated samples has also been studied to understand the domain structure and magnetoimpedance results.

Keywords : Giant magnetoimpedance, amorphous, microwire.

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1. Introduction

The large change in magnetoimpedance (MI), called Giant magnetoimpedance (GMI), in low magnetostrictive amorphous magnetic materials has recently been studied extensively [1,2]. When an ac current I_{ac} is applied to such materials, their impedance changes sensitively with the change in biasing dc magnetic field, H_{dc} . This property can be exploited for various applications such as in recording heads, micro-magnetic sensors and so on [3]. The field sensitivity of GMI can be as high as 100%/Oe [4] which is much higher than that observed in Giant magnetoresistance (usually less than 1%/Oe).

The origin of GMI is different in various frequency regions of the exciting ac current [2,5]. At low frequencies (~kHz) of the ac current, the field dependence of GMI is attributed to the inductive term of impedance $Z = R + j\omega L$. The time varying ac current produces a circular magnetic field that tends to change the corresponding component of magnetization. As a result, a voltage at the end of the sample is induced. With the application of a dc magnetic

field, this induced voltage and hence the inductance of the sample changes. If the frequency of the ac current is increased to MHz region, eddy current is developed and the ac current flows through a thin sheath near the surface of the sample due to skin effect [6]. The skin effect penetration depth δ is given by

$$\delta = \frac{1}{[\pi\sigma_c\mu_\phi f]^{1/2}} \quad (1)$$

where f , μ_ϕ and σ_c are respectively the frequency, circumferential permeability and conductivity of the sample. At a particular frequency, the application of a dc magnetic field changes the circumferential permeability μ_ϕ and hence the penetration depth δ which in turn changes the magnetoimpedance until the value of δ reaches the radius of the sample. In this frequency region where radius of the sample is much larger than the skin depth δ , both resistance and inductive component of total impedance Z depend on the permeability and contribute to the change in Z with magnetic field.

*Corresponding Author

The Co or Co-Fe based wire shaped samples with low magnetostriction coefficient are the prime candidate for generating GMI. These wire shaped samples consist of a single-domain core having magnetization direction closely parallel to the wire axis and a multi-domain external shell with transversely oriented magnetization (radial and circular for positive and negative magnetostrictive samples respectively). Recently, glass coated amorphous microwires with 10–25 μm diameter have drawn tremendous interest from the researchers because of their many useful magnetic properties such as their bistable hysteresis loop and large magnetoimpedance [5]. These microwires are found to be more promising for several applications compared to wires and ribbons because of their tiny dimensions, superior magnetic properties and protective glass coating. Very recently, GMI effect has been reported in a low positive magnetostrictive glass-coated $\text{Co}_{83.2}\text{Mn}_{7.6}\text{Si}_{5.8}\text{B}_{3.3}$ microwire [5].

Though the change in magnetization and tranverse permeability in the outer domains of the samples due to the application of a dc magnetic field is considered to be the main reason for GMI [2], no clear experimental evidence has been reported yet. To verify it, glass-coated $\text{Co}_{83.2}\text{Mn}_{7.6}\text{Si}_{5.8}\text{B}_{3.3}$ microwire has been heat treated by passing a dc current of 50 mA through it. This heat treatment increases the outer domain volume and hence the GMI value by inducing a transverse anisotropy. The magnetization of the as-quenched and heat-treated sample has been measured for better understanding of GMI results.

2. Experimental

Glass coated amorphous microwires of nominal compositions $\text{Co}_{83.2}\text{Mn}_{7.6}\text{Si}_{5.8}\text{B}_{3.3}$ were prepared by Taylor-Ulitovsky method [5]. An X-ray diffractometer (Siemens, Diffractometer-D5000) was used to check the amorphocity of the samples. The diameter of the metallic part of the sample, measured by an optical microscope, is about 18 μm and the thickness of the insulating glass coating is approximately 6 μm . A 12 cm long sample was used for the experiment. The impedance of the sample was measured by a spectrum/network analyzer (Hewlett Packard, 3589 A, 10 Hz–150 MHz) which was connected to a computer data acquisition system. An ac current of 1 mA was passed through the sample. The frequency of the ac current was varied from 0.1 MHz to 12.85 MHz. A Helmholtz coil system was used to apply a dc magnetic field along the axis of the sample during impedance measurement. The axis of the sample was kept perpendicular to the direction of the earth's magnetic field. The sample was heat-treated (hence forth termed annealed) by passing a 50 mA dc

current for different time durations, $t_{\text{an}} = 5, 10, 15$ and 25 min. The percentage change of MI with applied magnetic field is

$$\frac{\Delta Z}{Z}(\%) = 100 \times \left[\frac{Z(H) - Z(H_{\text{max}})}{Z(H_{\text{max}})} \right] \quad (2)$$

where $H_{\text{max}} = 140$ Oe, the maximum applied magnetic field. The hysteresis loops of as-quenched and annealed microwires were measured by induction method using a flux meter (Walker Scientific, MF3A).

3. Results and discussion

The field dependence of MI is shown in Figure 1(a) and (b) at 3.5 and 12.85 MHz frequency respectively with 1 mA

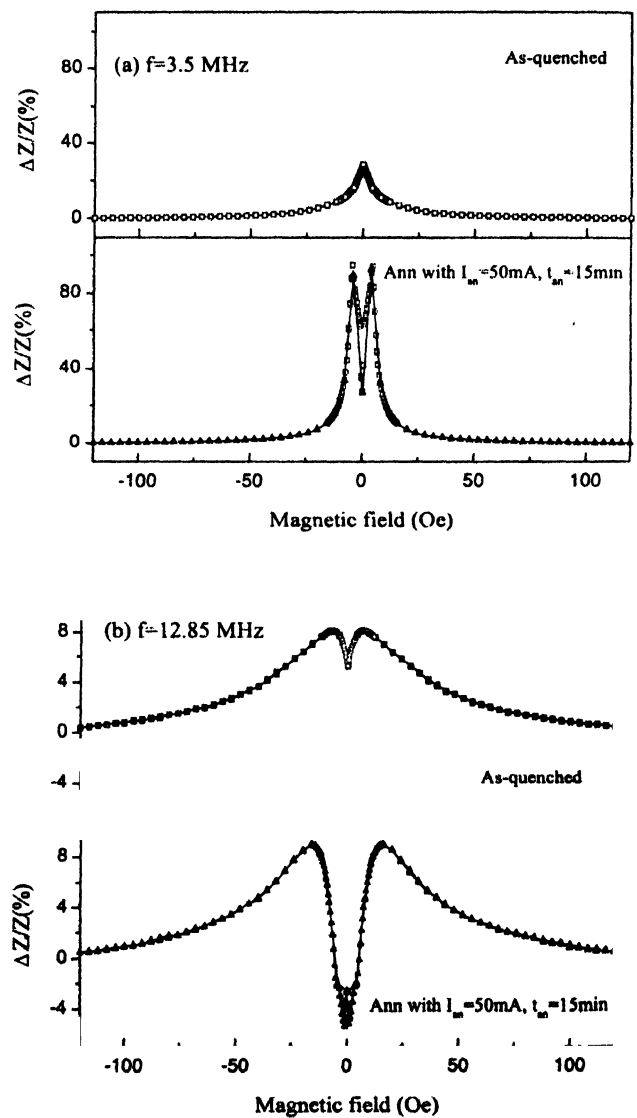


Figure 1. The variation of percentage change of magnetoimpedance $\Delta Z/Z(\%)$ with dc magnetic field H_{dc} of the as-quenched and annealed ($t_{\text{an}} = 15\text{min}$) sample with 1mA ac current at (a) 3.5 MHz and (b) 12.85 MHz frequency.

ac current. At frequency, $f = 3.5$ MHz (Figure 1(a)), the as-quenched sample shows single peak MI profile with the peak value $[\Delta Z/Z(\%)]_{\max}$ at $H_{dc} \sim 0$. The MI value increases drastically on annealing the sample by passing a dc current $I_{an} = 50$ mA. Maximum increase in MI value is observed when it is annealed for $t_{an} = 15$ minutes and the corresponding two peak MI profile at $f = 3.5$ MHz with $[\Delta Z/Z(\%)]_{\max} \sim 94\%$ is also shown in Figure 1(a). At 12.8 MHz (Figure 1(b)), the as-quenched sample shows two peak behaviour with much reduced MI value ($[\Delta Z/Z(\%)]_{\max} \sim 8\%$). On annealing the sample with $I_{an} = 50$ mA for different time durations, the peak value does not change much beyond 8 MHz.

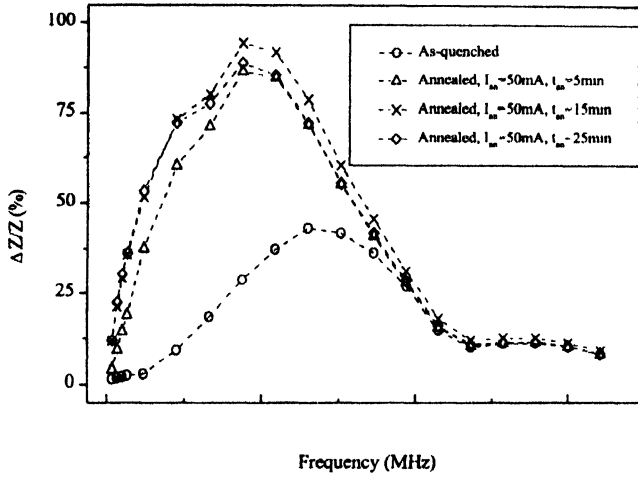


Figure 2. The variation of maximum percentage change in magnetoimpedance (i.e., the peak value of GMI), $[\Delta Z/Z(\%)]_{\max}$ with frequency of the as-quenched and annealed samples.

Figure 2 shows the frequency dependence of the MI peak value, $[\Delta Z/Z(\%)]_{\max}$ of the as-quenched as well as the annealed sample. At frequencies below 1 MHz, the MI value of the as-quenched sample is small. From the value of average transverse permeability $\sim 10^3$, the skin depth estimated from eq. (1) is comparable with the radius of the microwire when the frequency of the current is 1 MHz. This qualitatively explains the observed GMI due to skin depth above 1 MHz as shown in Figure 2 for the as-quenched sample. The field response of GMI of the as-quenched sample is maximum ($\sim 43\%$) around 5 MHz. The field response of GMI is improved when the sample is annealed with a dc current $I_{an} = 50$ mA. On annealing, MI value changes to a large extent even below 1 MHz (Figure 2) and the experimental results corresponds to $t_{an} = 15$ min show the best response with $[\Delta Z/Z(\%)]_{\max} \sim 94\%$ at 3.5 MHz.

The dc axial hysteresis loop of the as-quenched sample is shown in Figure 3. A sudden large change in

magnetization at very low field and a slow increase in magnetization at higher field is observed [7]. The hysteresis

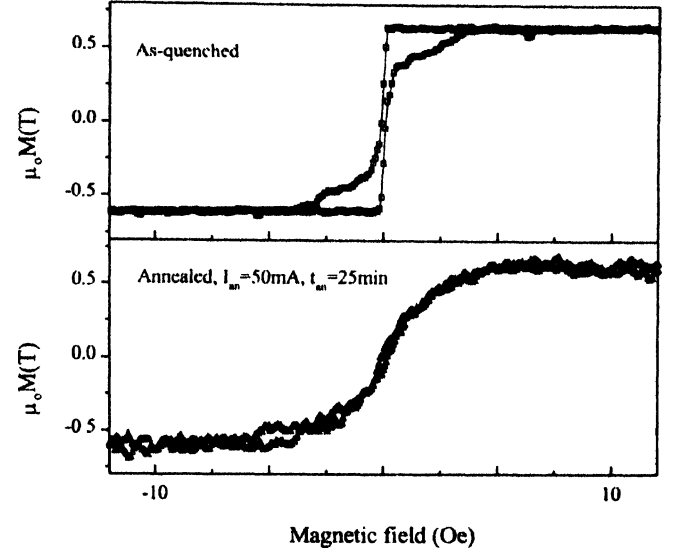


Figure 3. Hysteresis loops of the as-quenched and annealed sample ($I_{an} = 50$ mA and $t_{an} = 25$ min).

loop of the same sample annealed for 25 min with $I_{an} = 50$ mA has also been plotted in the same Figure. On annealing the sample, the initial jump in magnetization is reduced.

As mentioned before, the large change in MI in very low magnetostrictive amorphous magnetic materials is because of the change in penetration depth, δ due to the change in transverse permeability μ_{\perp} according to the eq. (1) by an external dc magnetic field H_{dc} [8]. The hysteresis loop and domain structure of the microwire suggests two permeability peaks [9] against magnetic field, one at the switching field of the inner core domain and the other near the anisotropy field of the outer shell. These two maxima in transverse permeability should give rise to two MI peaks on both sides of $H_{dc} = 0$. At lower frequencies, the anisotropy field is close to the switching field and the two peaks from the two domain regions can not be distinguished. As a result of it, single peak MI behaviour is observed (Figure 1) with the peak value at $H_{dc} \sim 0$ as the switching field of the microwire is very small (~ 70 mOe). With the increase in frequency of the ac current, the anisotropy field of the outer shell shifts more towards the higher field compared to the switching field as the domain wall displacement in outer shell is more affected by increase in frequency than the moment rotation in the inner domain [10]. This explains the higher values of ΔH_p , the separation between two peaks, at higher frequencies (Figure 1(b)).

As the annealing current generates a circular magnetic field during heating, a transverse anisotropy is developed within the sample resulting an increase in outer domain volume with magnetization direction perpendicular to the wire axis. As a result, the GMI value increases (Figure 1). The magnetostriction coefficient λ_s can be estimated using the expression $\lambda_s = (\mu_0 M_s / 3)(dH_k / d\sigma)$ and considering that the GMI peaks appears at the anisotropy field H_k . Taking $\mu_0 M_s = 0.7$ T, the value of λ_s for the sample annealed for 15 min is $\sim 4 \times 10^{-7}$.

4. Conclusions

Glass-coated amorphous microwire with nominal composition $\text{Co}_{83.2}\text{Mn}_{7.6}\text{Si}_{5.8}\text{B}_{3.3}$ and low positive magnetostriction coefficient are found to show giant magnetoimpedance effect in the range 1–8 MHz frequency. A maximum change of 43% in MI of the as-quenched sample has been observed at 5 MHz frequency. Heat treatment of the sample by passing a dc current of 50 mA through it enhances the MI value (maximum change $\sim 94\%$) by increasing the outer domain volume and inducing a transverse anisotropy. In case of as-quenched sample, the maximum value of MI is observed at $H_{dc} \sim 0$ when measured at frequency $f < 8$ MHz beyond which two peak MI profile is seen. The heat treated sample shows this two peak behaviour from a much lower frequency (below 1 MHz) and additional peaks at $H_{dc} \sim 0$ for $f > 10$ MHz. The

GMI results can be explained considering the skin effect at high frequency and the change in transverse permeability and hence the penetration depth with the change in applied dc magnetic field.

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References

- [1] K Mandal and S K Ghatak *Phys. Rev.* **B47** 14233 (1993)
- [2] L V Panina, K Mohri, K Bushida and M Noda *J. Appl. Phys.* **76** 6198 (1994)
- [3] M Vázquez, M Knobel, M L Sanchez, R Valenzuela and A P Zhukov *Sensor and Actuators A* **59** 20 (1997)
- [4] M Knobel, M L Sanchez, J Velazquez and M Vázquez *J. Phys : Condens. Matter* **7** L115 (1995)
- [5] K Mandal, S Puerta, M Vázquez and A Hernando *Phys. Rev.* **B62** 6598 (2000)
- [6] L D Landau, E M Lifshitz and L P Pitaevskii *Electrodynamics of Continuous Media* (Washington : Butterworth-Hinenann) p210 (1995)
- [7] L V Panina and K Mohri *J. Magn. Magn. Mater.* **157/158** 137 (1996)
- [8] R S Beach and A E Berkowitz *J. Appl. Phys.* **76** 6209 (1994)
- [9] D Menard, D Frankland, P Ciureanu, A Yelon, M Rouabhi, R W Cochrane, H Chiriac and T A Ovari *J. Appl. Phys.* **83** 6566 (1998)
- [10] D-X Chen, J L Munoz, A Hernand and M Vázquez *Phys. Rev.* **B57** 10699 (1998)